11-2003

Converting Plant Biomass to Fuels and Commodity Chemicals in South Africa: a Third Chapter?

L R. Lynd
Dartmouth College

H H von Blottnitz
University of CapeTown

B Tait
Sasol Technology

J de Boer
Sasol Technology

I S. Pretorius
University of Stellenbosch

See next page for additional authors

Authors
L R. Lynd, H H von Blottnitz, B Tait, J de Boer, I S. Pretorius, K Rumbold, and W H. van Zyl

Converting plant biomass to fuels and commodity chemicals in South Africa: a third chapter?

L.R. Lynd[a,b], H. von Blottnitz[c], B. Tait[d], J. de Boer[d*], I.S. Pretorius[e,f], K. Rumbold[a] and W.H. van Zyl[a†]

THERE HAVE BEEN TWO DISTINCT CHAPTERS in the history of converting cellulosic biomass to fuels and commodity chemicals in South Africa. The first chapter, from the late 1970s to the early 1990s, involved some of the most active research and development efforts of their kind anywhere in the world. Thereafter, during the second chapter, there has been very little activity in the field in South Africa while there has been an unprecedented awakening to the potential of biomass conversion elsewhere. This paper considers the rationale and possible benefits of a potential third chapter based on a revitalized effort on biomass conversion in South Africa. Such an enterprise would build on the country's large biomass production potential, strong technical capability in yeast biotechnology, a well-developed research and development infrastructure in biological processing, and expertise derived from the largest non-petroleum hydrocarbon processing industry in the world. Substantial societal benefits could be realized that address critically important national needs, including the utilization of sustainable resources, industrial development, and improved balance of payments. Moreover, establishing a modern biomass processing industry in South Africa appears to represent one of the largest potential sources of rural employment identified to date. We propose steps to realizing these benefits.

Introduction

Plant biomass currently provides a feedstock (raw material) for the production of fuels and commodity chemicals, but could do so on a much larger scale. Cellulosic biomass (such as grass or woody materials) is particularly well-suited for generating commodity products because of its low price and large potential supply as compared to grains or cane sugar. However, the recalcitrance (difficult to react) of cellulosic biomass makes it harder to process in a cost-effective manner than other plant feedstocks. Possible sources of cellulosic biomass include residues from the agricultural or forest products industries, and 'energy crops' grown primarily as industrial feedstocks. In the latter category, perennial grasses show particular promise in light of their potential for high productivity, compatibility with a broad range of sites, and beneficial contributions to soil fertility even under aggressive cultivation and harvesting.[1]

From the late 1970s to the early 1990s, South Africa's research and development (R&D) effort to convert cellulosic biomass to fuels and chemicals (called 'biomass conversion' hereafter) was among the largest anywhere, and in several respects can be said to have been ahead of its time. This period may be thought of as the 'first chapter' in the history of South Africa's pursuit of biomass conversion. During the second chapter, from the early 1990s to the present and with the threat of international sanctions removed, biomass conversion R&D has been largely dormant in South Africa. Over the same period, however, this field has received markedly increased attention elsewhere in terms of research, anticipated benefits, and commercial application. Moreover, the factors motivating this enhanced attention – sustainable and secure resource supply as well as economic and employment benefits – are directly relevant to South Africa today and in the future.

This paper considers the rationale, nature, and possible advantages of a potential third chapter of a revitalized biomass conversion programme in South Africa. We review the history of this activity prior to the early 1990s, and what happened subsequently in South Africa and elsewhere. An account of the reasons for investing in the high biomass conversion, with particular emphasis on its relevance to South Africa is followed by an outline of circumstances that have a bearing on possible future initiatives. These include current energy production and uses, biomass availability, South Africa's non-petroleum fuel industry, and R&D infrastructure. We conclude with recommendations on how the country might proceed from here.

Biomass conversion in South Africa prior to the early 1990s

As a response to both the continuing threat of economic sanctions as well as oil price shocks, South Africa aggressively sought to develop alternatives to petroleum-based fuels in the 1970s. The major Sasol oil-from-coal plants came on line during this period (see below), and a substantial interest in converting lignocellulosic materials to fuels and other products also emerged. In the 1970s, the Council for Industrial and Scientific Research (CSIR) began funding a comprehensive research programme focused on the utilization of lignocellulose, through the Cooperative Scientific Programmes, involving research institutes and universities. This work was consolidated in 1979 into a goal-orientated, multi-institutional enterprise focused on a single feedstock (bagasse), a single product (ethanol), and a single approach (enzymatic hydrolysis) to overcoming the recalcitrance of cellulose. The initial objective of the programme, to develop a technically and commercially viable process to convert bagasse into ethanol, was subsequently expanded to include production of single-cell protein.[2] In a parallel effort, research focused on developing yeasts expressing saccharolytic enzymes was begun in the mid-1980s at the University of Stellenbosch with support from the National Chemical Products (NCP) company of the Sentrachem Group. Additional initiatives targeted non-cellulosic feedstocks. These included expanded ethanol production by NCP, and a comprehensive research project, supported by the former Maize Board, at the former University of the Orange Free State that was aimed at producing ethanol from grain sorghum.

The CSIR-funded project involved, in addition to the National Food Research Institute, the universities of the Orange Free State, Cape Town, Natal, Durban-Westville, and Fort Hare, and the Sugar Milling Research Institute.[3] This programme recorded notable achievements over a ten-year period. These included enhanced production of cellulase enzymes on a pilot plant scale[4] and the discovery and characterization of new yeasts, such as *Candida shehatae* able to convert the pentose sugars derived from the hemicellulose fraction of bagasse to ethanol.[5–7]

[a]Department of Microbiology, University of Stellenbosch, Private Bag X1, Matieland 7602, South Africa.
[b]Thayer School of Engineering, Dartmouth College, Hanover, NH, U.S.A.
[c]Department of Chemical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, South Africa.
[d]Sasol Technology (Pty) Ltd, P.O. Box 5486, Johannesburg 2000.
[e]Institute for Wine Biotechnology, University of Stellenbosch, Victoria Street, Stellenbosch 7600.
[f]The Australian Wine Research Institute, Waite Road, Urrbrae, Adelaide, SA 5064, Australia.
*Present address: Holt, Campbell, Payton (Pty) Ltd, P.O. Box 7024, Cloisters Square 6850, Perth WA, Australia.
†Author for correspondence. E-mail: whvz@sun.ac.za

The Stellenbosch work on saccharolytic yeasts targeted conversion of lignocellulose or other insoluble biomass components into a product of interest in a single process step. Such consolidated bioprocessing (CBP) is applicable to a wide range of products and offers the largest potential cost reduction of any research-driven improvement in biomass processing analysed to date.[8] The Stellenbosch group has been amongst the most active worldwide in the CBP arena, as detailed in a recent comprehensive review.[8]

Strategic themes of the South African biomass conversion research and development effort prior to the early 1990s include biomass pretreatment and hemicellulose fermentation, the superior long-term potential of enzymatic hydrolysis compared to acid hydrolysis, and the potential breakthrough offered by CBP. The importance of these themes has been validated by recent analyses[9–13] and is much more widely accepted now than when they were adopted. While the South African biomass effort was strategically well-positioned, it was still small relative to the challenge of developing cost-effective technology to compete with oil refining. The disparity between the magnitude of this challenge and the South African effort was exacerbated by the country's relative isolation due to political and geographical factors. In addition, expectations for benefits in the short term became more difficult to satisfy after the sharp fall in world oil prices in the early 1980s.

Activity during the last decade

South Africa. One of the less-noted of the many changes culminating in the democratic elections in 1994 was the abandonment of biomass conversion as an active area of research and development in South Africa. The late 1980s and early 1990s saw targeted funding in this area drop essentially to zero. The bagasse programme of the CSIR and the Maize Board's sorghum project were terminated in 1991, and the NCP-supported work on polysaccharide-degrading yeasts came to an end in 1995.

Various factors contributed to ending support for biomass conversion research in South Africa in the early 1990s, and these differed somewhat according to the programme. Important among them was an understandable sense that the potential benefits of biomass conversion were of less immediate concern than improving services and opportunities for the majority of the population disadvantaged under apartheid. A second likely contributing factor was the feeling that the country had re-joined the community of nations, which was itself in the midst of a transition to a global economy, and chose not to continue supporting activities that were not competitive on the world stage. Developing and maintaining an ability to be self-supporting in the face of possible sanctions was a priority before the political changes of the early nineties, but not thereafter.

Like most South Africans, researchers who had been active in biomass conversion found themselves rapidly adjusting to new circumstances during the early nineties. The progressive elimination of funding that targeted biomass conversion for fuels and chemicals caused many researchers to shift their attention to other areas. Some who experienced such changes found ways to continue biomass-related work, often at a much reduced level, and many maintain strong personal confidence in the technical merit of biomass conversion.

Elsewhere. While South Africa turned away from biomass processing for fuels and chemicals in the 1990s, elsewhere there emerged an unprecedented appreciation of the potential of new applications in the field. The raised expectations and heightened activity concerning biological production of fuels and chemicals can be traced through a succession of visionary studies, actions on the part of industry, and increasing recognition of the potential of cellulosic biomass.

In 1992, Morris and Ahmed[14] foresaw a transition to a 'carbohydrate economy' involving enhanced production of chemicals and industrial materials from plant matter. A renewables-intensive energy scenario commissioned by the United Nations Solar Energy Group on Environment and Development as a contribution to the 1992 Rio Conference projected that biomass would become the largest energy source for the global economy during the 21st century,[15] and a preferred future energy scenario published by the Shell company in 1994 foresaw biomass utilization exceeding that of oil by 2060.[16] Lynd *et al.*[17] outlined in 1991 the potential of ethanol production from cellulosic biomass, including a distinctly positive balance of energy output relative to fossil energy input, and have subsequently updated consideration of this topic.[18,19] A 1995 study by the U.S. National Science and Technology Council[20] as well as several more recent studies[9,21] anticipate a 'second wave' of biotechnology applied to fields other than healthcare. In 1999, a report of the U.S. National Research Council entitled 'Biobased Industrial Products'[21] anticipated that 'biological sciences are likely to make the same impact on the formation of new industries in the next century as the physical and chemical sciences have had on industrial development throughout the century now coming to a close.' This report projected also that by 2020 biomass-based processes would account for 10% of fuel production, 25% of organic chemical production, and 95% of organic material production in the U.S., with increasing contributions thereafter. Recent studies[12,21] anticipate the emergence of industrial facilities featuring integrated production of fuels, chemicals, and power from biomass in 'biorefineries' reminiscent of today's oil refineries. It is anticipated that such co-production will offer substantial economic benefits compared to the dedicated production of single products.

Following the emergence of health-care-related biotechnology as a major industrial sector in the 1980s, the biological manufacture of commodity products (such as fuels and bulk chemicals) went from peripheral to central in the thinking and activities of a substantial number of large businesses during the 1990s. The U.S. chemical industry has restructured itself in the wake of the biotechnology revolution[22] by means of billions of dollars of investment, the formation of joint ventures, and creation of life-science-orientated spinoffs of a size comparable to their parent companies.[23] Major development efforts have led to, or are in the final stages of leading to, commercial processes for the manufacture of new commodities such as polylactic acid by Cargill Dow and 1,3-propanediol by DuPont,[24] with other products in various stages of development by several companies. William Frey, business director for DuPont's science and technology division, has called industrial biotechnology 'a key growth engine in the 21st century'.[25]

Although maize is the main feedstock for commercial manufacture of biomass-based commodity products today, the advantages of lignocellulose feedstocks are widely recognized by both the industrial and academic communities. These advantages include low cost, large potential supply, and favourable environmental attributes.[9,19] Several small companies are dedicated to commercial application of technology for converting cellulosic biomass, and larger concerns are following developments closely in this area. Among the bigger establishments, chemical companies are most involved in biomass conversion rather than the oil and energy industries. However, major oil companies are increasingly aware of the potential need and opportunities in the area of renewable energy in general[26] and biomass conversion in particular.[27] The recent substantial investment of Shell in Iogen, a Canadian company targeting ethanol production from cellulose, is particularly noteworthy.[28] Whereas U.S. companies have invested most in biomass conversion for the production of chemicals, interest in energy applications has been greatest from businesses based in Europe such as Shell and BP/Amoco.

Cellulosic biomass would likely be the preferred feedstock for fuel and commodity chemicals today were it not for the difficulty of converting cellulosic feedstocks into reactive intermediates, that is, overcoming the recalcitrance of the cellulose. Research to convert cellulosic biomass is being pursued around the world, with the U.S., Canada, and several EU countries particularly active. The recalcitrance of cellulosic biomass can be overcome by gasification, acid hydrolysis, and enzyme-mediated hydrolysis. Of these approaches, the last is expected to be the most cost-effective in the long run.[9,10] Ways to lower the cost of enzymatic hydrolysis include improving cellulase enzymes, developing microorganisms suitable for consolidated bioprocessing (see above), and improving processes for 'pretreating' cellulosic biomass to make it more amenable to enzyme action. Even if the potential of enzymatic processing is realized, gasification also appears to have an important role to play. For a typical lignocellulosic feedstock, about 40% of the energy present in the original biomass remains in lignin-rich residues present after enzyme-mediated hydrolysis and fermentation. As shown in Fig. 1, gasification of these residues with subsequent conversion to energy, chemicals, fuels or a combination of these is a potentially important means of deriving added value from cellulosic feedstocks while also significantly improving resource utilization efficiency.

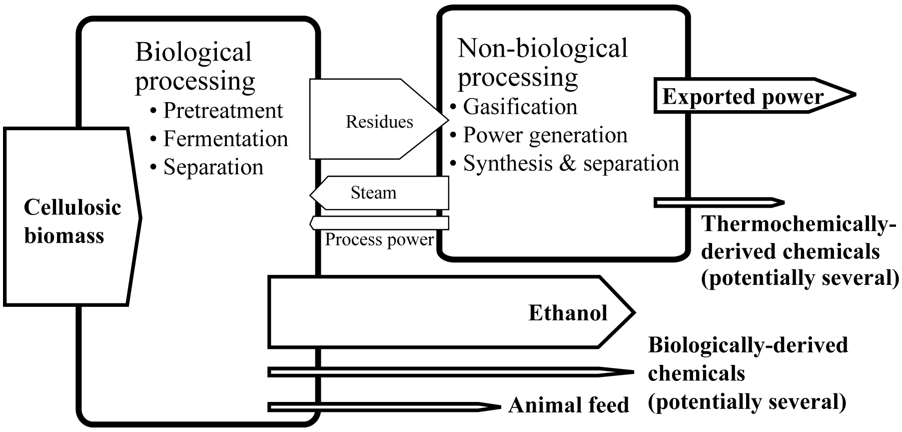

Fig. 1. Processing of cellulosic biomass with complementary application of biological processing and non-biological processing featuring gasification. The width of the horizontal arrows is roughly proportional to energy flows for mature technology, although such flows depend on the mix of products generated.

Reasons for increased interest in biomass processing

Sustainable and secure supply of resources and the realization of economic benefits motivate increased worldwide interest in biomass conversion for fuels and chemicals.[19] These themes are relevant to South Africa today in ways that reflect the country's particular circumstances.

Sustainable and secure resource supply. Plant biomass is the sole foreseeable sustainable source of organic fuels, chemicals, and materials,[9] and is also a potential renewable source of electrical power. The production and consumption of fuel and power account for the lion's share of non-renewable resource depletion as well as pollution and emissions of greenhouse gases, and are thus particularly important and demanding in the context of a transition to a sustainable economy. South Africa has no significant indigenous oil resource. Coal is abundant, and domestic natural gas reserves are modest, with commercially exploitable reserves also in Mozambique and Namibia. Imported oil provides about two-thirds of the motor fuel used by South Africa's transportation sector, with the balance provided by synthetic fuels based on coal and gas feedstocks. Production of transport fuel from sources other than petroleum protects the country's economy to some extent from fluctuations in the price of crude oil. The government has indicated through both the Treasury[29] and the Department of Minerals and Energy[30] that it wishes to extend protection from high crude oil prices through fuel production technologies which invest in rural development and employment.

South Africa is a signatory to the Kyoto Protocol, and it is the government's stated intention to make the country's due contribution to the global effort to mitigate greenhouse gas emissions.[30] Although South Africa is not obliged to stabilize or reduce carbon emissions, it stands to gain substantially by investing in projects that result in reduced carbon emissions. In addition, concerns over global climate change are at odds with expanded use of coal for the production of synthetic fuels, as well as electrical power, in view of the large greenhouse gas emissions associated with coal compared with gas and oil. By contrast, biomass conversion has the potential to result in a sustainable carbon cycle, with photosynthetic production of biomass removing from the atmosphere the same amount of CO_2 that is returned upon conversion and combustion (Fig. 2). Several studies conclude that large reductions in greenhouse gas emissions can be realized from processes based on cellulosic biomass.[17,,31–34] To our knowledge these conclusions have not been challenged.

'Oil is a magnet for conflict', observed

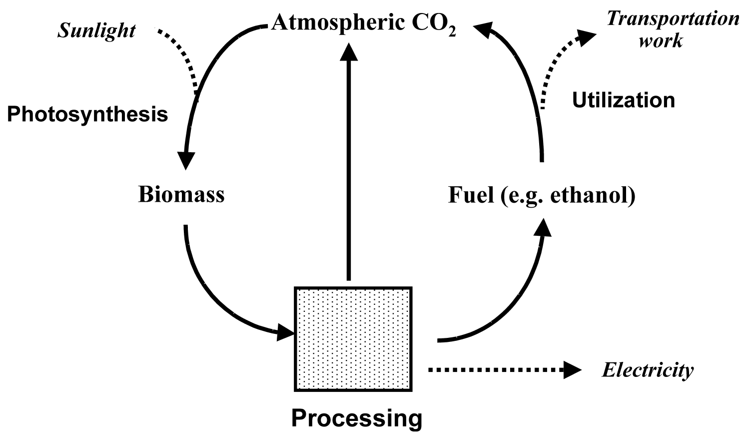

Fig. 2. The potential for a sustainable carbon cycle for processes based on cellulosic biomass (illustrated here for transportation, adapted from Lynd *et al.*[17]).

U.S. Senator Richard Lugar and James Woolsey, former director of the U.S. Central Intelligence Agency.[35] 'If a transition from fossil fuels to biofuels becomes affordable,' they continue, 'the world's security picture could be different in many ways. It would be impossible to form a cartel that would control production, manufacturing, and marketing. The ability of oil-exporting countries to shape events would be increasingly limited.' In particular, such a transition would allow the world's dealings with oil-rich countries of the Middle East to be guided by conflict resolution uncomplicated by the competing objective of maintaining oil supplies.[36,37]

Economic and employment benefits. Just as 'the Stone Age did not end because we ran out of stones', opportunity may prove to be an equal or more important driver for expanded use of biomass compared to scarcity, limited sustainability, and insecure supply. The South African government has recognized that the driving force for diversifying energy supply in South Africa has shifted from self-sufficiency to sustainability and increased opportunities for energy trade, particularly within southern Africa.[30]

Cellulosic biomass is available as both residues and dedicated crops at a lower price in terms of energy than is oil.[9] We think it likely that opportunities exist in South Africa to apply biomass conversion technology in the near term. In the longer term, we foresee research-driven advances lowering the cost of this technology to the point where fuels and commodity chemicals can be produced from biomass at prices competitive with fossil resources today.

Imports of crude oil and petroleum derivatives were worth R 33.7 billion in 2002, which represented 12% of total imports of all kinds and were among the largest contributors to the flow of currency out of South Africa.[38] Although improved balance of trade has been cited as a reason for deploying biomass-based technologies in developed countries such as the U.S., the potential benefits of improved balance of trade via indigenous production of biomass-based fuels are far more important in an African context, where there often is little capacity to produce enough high-value exports to compensate for high-volume petroleum imports. Issues associated with trade imbalance and currency devaluation are almost certain to become more critical if oil supplies tighten and prices rise over the coming decades, as has been predicted.[39–41] This country will be well-served if it responds to these prospects in a proactive rather than reactive manner.

In many countries, both rich and poor, the economic viability of rural communities based on farm income is precarious at best, and would benefit from new markets for agricultural goods produced sustainably. Biomass conversion represents a potentially significant source of rurally based employment for unskilled workers involved in production, harvesting, and gathering of plant matter, as well as semi-skilled and skilled workers at conversion facilities. Opportunities for unskilled labour are particularly good for products such as fuels and commodity chemicals, for which large amounts of feedstock are required. Such opportunities would help to alleviate the decline in the number of jobs in mining and agriculture, both major sources of employment for the unskilled workforce, experienced over the last two decades in South Africa.[42] Because of the relatively diffuse nature of the biomass resource – as compared to coal, for example – biomass conversion facilities are expected to gather feedstock from a radius of up to 100 km and could potentially be widely distributed in regions with adequate rainfall to achieve significant rates of plant growth.

Job creation through biomass conversion has been quantified in a study of ethanol production from maize in the United States by Petrulis *et al.*[43] The authors estimate job creation from a new 380 million litre per annum (8 PJ/yr; 1 PJ = 10^{15} joules) ethanol production facility at 370 temporary jobs during construction, 840 new jobs during the operational phase (including jobs directly involved in ethanol production as well as indirect job creation), and 1340 new jobs in feedstock production. We expect that the 2180 permanent and 370 temporary jobs needed in America would be substantially more in South Africa due to the more labour-intensive working conditions here. A doubled rate of job creation in South Africa, corresponding to 4360 new permanent positions for a facility of the same size, or about 550 jobs per PJ of annual fuel production, appears a reasonable estimate. More detailed consideration of new employment opportunities from biomass conversion appear warranted. In light of the large amounts of biomass potentially available in South Africa (discussed below), establishment of an advanced biomass-processing industry has the potential to be one of the biggest sources of rural employment. As a rough illustration, conversion of half of the estimated agricultural and forestry residues produced annually in South Africa to liquid fuels at a 50% efficiency and at the rate of 550 jobs per PJ annual fuel production would create about 27 400 jobs, corresponding to a 2.9% increase in the agricultural workforce. The opportunity to create employment by converting energy crops is potentially an order of magnitude larger, but will likely take longer to realize.

During the first industrial revolution, oil played a central role in determining world events and the economic well-being of nations, companies, and individuals.[44] If the 21st century is to be marked by a second industrial revolution featuring a transition to sustainable energy sources and increased efficiency of resource use,[45] then the new enabling technologies can be expected to have a similarly large impact. As the transition from non-sustainable resources to sustainable resources progresses, we suspect that international trade in energy per se will become less important while trade in energy conversion technology becomes more important. Technologies for converting biomass and other indigenous energy sources represent a technology export opportunity of historical proportions.

The current situation

Energy supply and utilization. Of the 4200 PJ of primary energy supplied annually in South Africa, over 80% is based on coal (Table 1). The next largest energy source is crude oil at around 10%, the bulk of which (>80%) is imported, followed by renewable energy at approximately 5% of primary energy or 9% of total energy consumption. Most current renewable energy comes from biomass used by households in relatively low-efficiency devices (such as open fires), or by agro-processing and pulp and paper industries to generate process heat from waste

Table 1. Energy supply and consumption in South Africa in 2000/01 [in units of PJ/yr(%)].

Source		
Coal	3400	(82)
Crude oil	410	(10)
Renewable energy	~200	(5)
Nuclear energy	47	(1)
Natural gas	80	(2)
Total	4170	
Consumption		
Industry	1314	(59)
Transport	584	(26)
Households	268	(12)
Agriculture	85	(4)
Total	2250	

Supply and consumption totals are not equal owing to inefficiencies associated with conversion and transmission (as in electrical power generation, coal refining).
Data compiled from refs 30, 46.

products, with a small contribution from hydropower for electricity generation. Conversion of primary energy to useful energy products involves significant energy losses, with coal-based electricity generation and synthetic fuels production both reporting thermal efficiencies well under 40%. Of the 2300 PJ of energy utilized, some 700 PJ of electricity and 640 PJ of liquid fuels form the largest proportions, followed by direct use of coal and biomass, both in industry and in the home.

Of the 580 PJ/yr used in transportation, the bulk is provided by liquid fuels, of which imported crude oil represents some 60%. The other 40% of synthetic fuel is produced from coal and, increasingly, natural gas. Diesel sales grew by 25% between 1995 and 2002, while petrol sales have remained more or less stagnant.[49] The use of lead as a petrol octane enhancer is being phased out during the coming decade in South Africa and across the African continent. Ethanol, one of several octane-enhancing fuels that can be produced from biomass, is a potential option as an octane-boosting replacement for lead in low-level (for example, 5%) ethanol–petrol blends.

Biomass availability

Residues. For every dry tonne of cane sugar, grain (such as maize and wheat) or seeds (for instance, sunflower), roughly a tonne of cellulosic residue is produced on a dry basis. Thus the largest flows of cellulosic residues stemming from agriculture in South Africa are associated with the crops produced in the largest volume: maize and sugar cane. The forestry industry is a further significant potential source of residual biomass. The production potential of biomass residues (wood, agricultural, grass) is broadly distributed in South Africa, with the greatest quantities available in the eastern third of the country.[50]

The feasible availability of cellulosic residues for use as industrial feedstocks is less than the gross production. One reason for this is that using residues for industrial feedstocks must compete in many cases with existing uses. For example, all of the cellulose-rich bagasse remaining after cane pressing is used in some fashion by the South African sugar industry, with most of it burned to provide process steam and (in some cases) power for internal consumption.[51] There are, however, opportunities to increase the efficiency of steam and power generation from bagasse so that energy requirements of the mill can be satisfied with substantial additional capacity available for export.[52] Net energy production in excess of internal demand by the South African sugar industry could take the form of electrical power, fuel (such as ethanol), industrial chemicals, or a combination of these. There are likely strong economic advantages to co-producing fuel and power, consistent with the notion of a multi-product biomass refinery (see above).

A further reason that the feasible recovery of residues is less than gross residue production arises from the need to maintain soil fertility, which for many cropping systems requires returning a fraction of agricultural residues to the soil. A recent analysis by Sheehan *et al.*[53] focusing on maize production in the U.S. found that the fraction of stover (consisting of the above-ground plant parts exclusive of the grain) that can be removed while maintaining constant soil carbon varies widely from 13% to 70%, depending on the mode of cultivation. Allowable removed fractions are toward the low end of this range for current cultivation practices but can be much higher if alternative methods, such as no-till planting, are followed. The sensible fraction of stover removal has not to our knowledge been examined in terms of climate, soils, and agricultural practices in South Africa.

Residues provide an excellent point-of-entry and proving ground for biomass conversion on a commercial scale because they are in many cases already collected and available at low, or in some cases perhaps negative, cost. The potential of residues in this context is not necessarily proportional to their scale of production. For example, waste sludge produced at paper mills may be particularly attractive amongst cellulosic feedstocks because many sludges are highly amenable to enzymatic hydrolysis without pretreatment.[54] Beyond their role in launching a biomass processing industry, responsibly harvested residues could be a significant and desirable contributor to overall energy supply in their own right.

Energy crops. Energy crops appear to have great potential to contribute to energy supply and environmental quality, assuming that management practices are sensitive to considerations such as maintaining soil fertility and wildlife habitat. We acknowledge the importance of such practices in the revitalized biomass conversion effort we recommend. Marrison and Larson[55] have conducted the most detailed analysis known to us of the potential of energy crop production in Africa. Their study is instructive with respect to both specific findings and also the general issues involved. The approach taken by these authors involves calculating land area exclusive of cropland, forest land, and wilderness areas, and estimating energy crop yields based on the mean of annual precipitation at different locations in each country and a correlation based on data from commercial biomass plantations in Brazil taken mostly in the 1980s.[56] Land requirements for food production in 2025 are estimated based on anticipated cereal crop yields and population growth. The non-crop, non-forest, non-wilderness land category upon which Marrison and Larson's study is based includes land that is now devoted to livestock production. Thus, it is probably most appropriate to consider relatively low fractional utilization of this land (for example, 5–20%), and there is a need to analyse the compatibility of integrating energy crop and livestock production at a local level in light of cultural as well as economic factors. Studies on conditions in the United States indicate that such integration affords opportunities for substantial synergies (B. Dale, pers. comm.), and doubtless would be worth conducting in South Africa.

For Africa as a whole, the energy benefit of producing cellulosic biomass in the year 2025 at a cost ≤$3/GJ (corresponding to about U.S.$17 per barrel of oil) is estimated at about 1700 PJ per percent non-crop, non-forest, non-wilderness land planted in energy crops. Thus, if 5% and 20% of such land were planted, the estimated returns are 8500 PJ and 34 000 PJ, respectively. This may be compared with Africa's total commercial energy use of approximately 10 000 PJ in 1995. For South Africa, the estimated gross (prior to conversion) annual biomass energy production potential is about 135 PJ per percent of available non-crop, non-forest, non-wilderness area used to produce energy crops. Thus in the base case estimate of Marrison and Larson – entailing use of 10% of non-crop, non-forest, non-wilderness land – the estimated production potential is 1350 PJ. This is the greatest potential of any country in Africa.

The long-term potential of biomass to provide energy-related services cannot be realistically portrayed as a single number, but rather is a highly and perhaps surprisingly variable quantity which depends on both technical and societal factors.[19,57,58] In addition, both limitations and opportunities can arise that are not evident from a more general consideration when biomass supply is examined in detail for a particular country or region. Consistent with this, Marrison and Larson caution that their analysis is preliminary, suggest that more detailed country and regional assessments would be worthwhile, and acknowledge the dependence of their results on various assumptions. For example, the correlation used for energy crop production in relation to rainfall based on Brazilian data might not be applicable, and could indeed be lower, for South Africa. Moreover, large R&D-driven improvements in the productivity of energy crop production are possible but are not incorporated into Marrison and Larson's calculations. As a second example, estimates of the land remaining after allowance for food production depend on growth in both population as well as cereal crop yields, either or both of which could be higher or lower than that assumed by Marrison and Larson. Notwithstanding these limitations, Marrison and Larson regard as robust the conclusion that Africa as a whole has significant biophysical potential for producing biomass energy.

Invasive plants. The presence of invasive alien plants has emerged in recent years as a matter of pressing concern. In the Western Cape in particular, non-native *Acacia,* as well as other species are seen as a threat to the unique fynbos ecotype. In 1995, the Working for Water programme was started by the Department of Water Affairs and Forestry, with the aim of removing invasive plant species in order to: (i) prevent the loss of biodiversity due to displacement of indigenous flora, (ii) avoid groundwater loss from increased evapotranspiration by invasive plants, (iii) regain potentially productive land for grazing and livestock production, and (iv) control increasing costs for fire protection. More than R 1 billion has been spent on this effort to date, which has included more than 300 projects providing cumulative employment for 21 700 people as of the end of the 2000/01 financial year.[59,60] Collected biomass is converted to woodchips and charcoal, for which current demand totals about 145 000 tonnes.[60] This is far less than the standing mass of invasive species in South Africa, which has recently been estimated at 8.7 million dry tonnes and could double within 15 years if uncontrolled.[61]

Use of invasive plant species as feedstocks for biomass conversion to fuels and commodity chemicals offers the prospect of providing an unusual multiplicity of benefits, including preservation of South Africa's unique species diversity, provision of employment opportunities for unskilled labourers, and making available large quantities of low-cost feedstock for industrial processes. As with paper sludge (see above), use of invasive plant species could be particularly advantageous in overcoming cost-barriers associated with first-of-a-kind technology.

Potential energy contribution. Data on biomass availability in South Africa are compiled in Table 2. The value shown in bold for total annual production, 1470 PJ/yr, corresponds to over one-third of total energy used in South Africa today, and if converted at 50% efficiency to liquid fuels would provide 125% of the country's current energy use in the transport sector (Table 1). The total of 300 PJ/yr associated with residues is about 7.5% of current primary energy consumption. Our estimates for residual cellulosic biomass availability in South Africa are in general comparable to, and in some cases somewhat less than, independent estimates made in a collaborative study by CSIR, Eskom, and the Department of Minerals and Energy.[30] Commercially significant volumes of industrial chemicals can be manufactured using quantities of feedstocks that are small relative to those required to make an impact on satisfying energy needs, but still offer substantial development and employment benefits.

The data in Table 2 indicate that biomass is potentially available in South Africa on a scale that is significant relative to current and foreseeable energy demand. However, we caution against interpreting these data in absolute terms in light of considerations discussed above. In particular, the energy values listed in Table 2 are likely to be an overestimate of what could be available in practice for residues. For energy crops, there are factors that could make the values listed in Table 2 both higher and lower. More detailed study of South Africa's biomass production potential is warranted in light of both the promise and uncertainties associated with available information.

South Africa's non-petroleum fuel industry. Built on government commitment and a clear vision for what it sought to accomplish, Sasol provides a model for establishing a commercial biomass conversion industry and could potentially play an important role establishing such an industry in South Africa. The history of Sasol[66] started with the lessons of the Second World War, where the dearth of indigenous petroleum reserves exposed South Africa to risk from global energy (and economic) uncertainty. This experience together with the country's vast reserves of low-grade (high ash) coal led to the establishment in the 1950s of oil-from-coal facilities on a modest scale at Sasolburg. After the first oil crisis in the early 1970s, a commitment was made for significantly larger commercial facilities – with Sasol II being commissioned at Secunda in 1980 at 50 000 barrels per day. This was a 10-fold scale-up from the Sasolburg plant. The 1979 revolution in Iran which deposed the Shah, and again escalated international crude oil prices, led to a decision to 'double' the facility – with Sasol III being commissioned in 1982. Over the past 20 years, production has increased by over 50%. The initial emphasis on liquid fuels has increasingly switched to value-added chemicals, which currently comprise over 30% of production volumes. This concept of starting with a low market risk product (energy), and evolving to a more diversified product slate with increased production of high-value products is likely to be applicable to biomass as well as coal.

Sasol's overall energy and chemical sales are just below 300 PJ/yr, which makes the South African non-petroleum hydrocarbon processing industry the largest in the world – albeit by a narrow margin (Fig. 3). Established Sasol facilities provide an industrial infrastructure orientated to commodity products and could thus be

Table 2. Summary of data relevant to biomass availability in South Africa [in units of Mt/yr (energy equivalent in PJ/yr)].

1. Residues		
Agricultural[a]		
Maize stover	6.7	(118)
Sugar cane bagasse	3.3	(58)
Wheat straw	1.6	(28)
Sunflower stalks	0.6	(11)
Subtotal	**12.3**	**(214)**
Forestry industry[b]		
Left in forest	4.0	(69)
Saw mill residue	0.9	(16)
Paper & board mill sludge	0.1	(2)
Subtotal	**5.0**	**(87)**
2. Energy crops[c]		
From 5% of available land	34.0	(584)
From 10% of available land	**67.0**	**(1170)**
From 20% of available land	134.0	(2330)
Total, annual basis (assuming 10% available land)	**84.0**	**1470**
3. Invasive plant species[d]	**8.7**	**(151)**

[a]Maize, wheat, and sunflower based on 5-year averages as reported in the 2003 National Department of Agriculture (NDA) crop production estimates,[62] assuming that residue production is equal to crop production and that grains are harvested at 25% moisture content. Bagasse based on NDA production data using yield factors from ref. 63.
[b]Forest product residues data based on total roundwood sales from plantations,[64] assuming 50% moisture content, 50% of harvested logs left in the forest, and 50% loss in milling. Paper sludge based on 5% of total annual South African paper and paper board production of 2.3 Mt.[65]
[c]Based on the value for 10% of available land area calculated by Marrison and Larson[55] with available land being land in excess of cropland required for food production (estimated for 2025), and land currently in use as forest or wilderness.
[d]From Theron.[61]

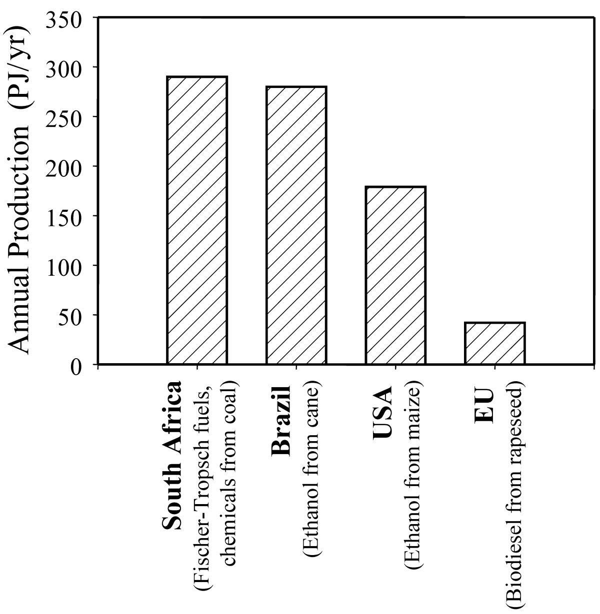

Fig. 3. Annual production of non-petroleum hydrocarbon processing industries worldwide. Data for 2002: South Africa (Sasol), 290 PJ; Brazil, 280 PJ (ref. 67); U.S.A., 179 PJ (ref. 68); EU, 42 PJ (ref. 69).

suitable sites for the next generation of biomass-based plants, including demonstration and pilot facilities. In addition, Sasol's methods for gasification, synthesis, and separation technology developed for coal can readily be applied to biomass feedstocks, either on a stand-alone basis or in combination with biological processing (Fig. 1). Finally, there are potential synergies between existing Sasol products and markets and those that could be developed based on biomass. For example, Sasol brings application know-how relevant to fuel ethanol, for which production is presently limited by supply. Expansion into biomass processing would provide Sasol with a new business opportunity that builds on existing strengths, has scope to expand independent of factors that limit the application of coal processing, and is responsive to international calls for increased sustainability. For these reasons, Sasol is evaluating a return to the biotechnology arena with a focus on commodity products from low-cost biomass feedstocks.

R&D infrastructure. A considerable R&D infrastructure exists in South Africa that could support a revitalized effort in biomass conversion. Sasol is one significant contributor to this infrastructure, as noted above. In addition, and notwithstanding the decline in R&D support during the early 1990s, expertise and facilities in commodity-orientated biotechnology and bioprocessing built in the 1980s, primarily anticipating the manufacture of fuels and chemicals, has been maintained and in some cases even expanded in the 1990s for other applications. For example, research groups at the universities of the Free State, Natal, and Durban-Westville, and at Durban Institute of Technology,* are investigating use of lignocellulosic microorganisms and their enzymes in the pulp and paper industry. Smaller related activities are under way at the universities of the North, Rhodes and Stellenbosch as well as the CSIR. Much of this work has been conducted with support of the paper and pulp industry, based primarily in KwaZulu-Natal, with the purpose of reducing the use of bleaching chemicals and alleviating pollution.

Applied microbiology, and yeast biotechnology in particular, is a noted strength of the South African R&D portfolio. The Department of Microbiology and Biochemistry at the University of the Free State has 25 years of experience in the use of continuous cultures and microbial physiology, especially yeast physiology. A long-standing interest is the fermentation of D-xylose to ethanol using yeasts, with additional activity in the area of producing xylanases and laccases by filamentous fungi and yeasts. The University of Stellenbosch is engaged in wine biotechnology and is also exploring use of saccharolytic enzymes for animal feed production. In addition, development of saccharolytic yeasts for CBP continues at a modest pace with support from the United States as part of a collaboration with Lynd's laboratory at Dartmouth College.

In the area of biochemical process engineering, the CSIR's Bio/Chemtek group in Modderfontein, Johannesburg, has a state-of-the-art fermentation piloting facility and associated expertise that is unique in South Africa as well as the African continent. This group, formed in the mid-1980s by African Explosives and Chemical Industries (AECI) and wisely continued after incorporation into the CSIR in the mid-1990s, represents a potentially important resource in the context of a revitalized biomass conversion effort. Although chemical and process engineering departments at South Africa's universities have traditionally been orientated towards metallurgical applications, involvement in biological applications is significant and expanding. The Department of Chemical Engineering at the University of Cape Town has had a long-standing interest in commodity bioprocessing, and research studies and coursework in this area have recently begun at the University of Stellenbosch. Regional initiatives in the Western Cape and Gauteng seek to provide seed funding, information exchange, and networking with the overall goal of fostering employment and economic development via expansion of South African biotechnology industries. Biotechnology applications involving biomass conversion are particularly well-suited to meeting these goals in light of the great potential for cost reductions, attractive return on investment, the possibility of deployment on a large scale, and likely creation of jobs for skilled workers and for the unskilled (for example, in feedstock production, harvest, and transport). South Africa could play a leadership role in this field, given the relative size and state of advancement of this activity here and around the world.

This argument is more difficult to make with respect to biotechnology applied to healthcare, where South Africa's activity is dwarfed by large efforts elsewhere.

The case for a 'third chapter'

A revitalized South African effort involving research, development, demonstration, and commercialization in the biomass conversion field could provide significant benefits in terms of sustainable resource supply, improved balance of payments, and both rural and industrial economic development. On the world stage, South Africa is uniquely positioned to pursue biomass conversion

*Several tertiary education institutions in South Africa, referred to in this article, have changed their names recently. Thus, the former University of the Orange Free State is now the University of the Free State, the University of Durban-Westville merged with the University of Natal, which, since January 2004, is called the University of KwaZulu-Natal. The Natal Technikon merged with the M.L. Sultan Technikon and the combined institution is now the Durban Institute of Technology.

in light of the country's large biomass production potential, the presence of advanced industrial and transportation infrastructures together with pressing needs for rural employment, and technical strength in the key areas of gasification technology and applied microbiology. The possibility of South Africa playing a pioneering role in the biomass conversion field deserves serious consideration in our view. The realism of this goal is supported by the country having played such a role previously with respect to both coal gasification and conversion as well as fermentative production of solvents (acetone, butanol and ethanol).

Such a revitalized effort would be aligned with policies and strategies articulated by government in recent forums. In the Department of Minerals and Energy's draft white paper on the Promotion of Renewable Energy and Clean Energy Development,[30] a framework is presented within which the renewable energy industry can operate, grow and contribute to the local economy and the global environment. To get started on a deliberate path towards this goal, the government's medium-term (10-year) target is that the share of final energy consumption that is provided by renewable energy should increase by 10 000 GWh (36 PJ/yr) by 2012. It is envisaged that this increase will come mainly from biomass, wind, solar and small-scale hydropower. Biomass-derived fuels such as biodiesel, bioethanol and landfill gas are identified as key focus areas. The white paper recognizes the need to create an enabling environment through the introduction of fiscal and financial support mechanisms within an appropriate legal and regulatory framework so that renewable energy technologies can compete with fossil-based technologies. Details of these measures are expected to emerge in 2004. The *National R&D Strategy*, prepared under the auspices of the Department of Science and Technology and approved by Cabinet in 2002,[70] identifies five strategically important R&D missions: science and technology innovation for poverty reduction, biotechnology, innovation in the resource-based industries, information technology, and advanced manufacturing strategies. Biomass conversion is directly responsive to the first three of these.

The proposed 'third chapter' of South African involvement in the biomass conversion field need not be self-contained as was the case in the 1970s and 1980s. Rather, a much more advantageous approach would be to develop the country's strengths and form partnerships with corporations, institutions, and individuals around the world that have complementary strengths. This collaborative approach would provide a means to leverage both technical know-how and financial resources, and thus enable more rapid progress at lower cost than a self-contained effort. With good planning and execution, South Africa can reasonably expect to be a valuable and equal partner in biomass-ralated initiatives.

As steps toward a revitalized South African effort in the biomass field, we recommend:

1. Perform a detailed analysis of biomass availability as well as the potential of biomass to meet energy supply, economic development (including rural development and job creation), and sustainability objectives in a national context. The analysis should consider both the near term, for instance, contributions to achieving the first renewable energy target through the application of commercialization-current technologies under-utilized biomass resources, and the longer term, in which processing of cellulosic feedstocks is carried out on a scale sufficient to make a substantial impact on 'mega-issues' such as energy supply and the balance of payments.
2. Mount an initiative to bring technical strengths to bear on biomass conversion applications. Although there is South African expertise in biomass gasification and applied microbiology, it is being applied to biomass processing to a very limited extent. Development of a focused, coordinated effort in biomass processing should be incorporated in the national R&D strategy, with attention given to integration of this effort into the technology missions to which it responds: science and technology innovation for poverty reduction, biotechnology, and innovation in resource-based industries.
3. Identify and implement activities fostering development of a biomass processing industry in South Africa. Such activities include identification of near-term application opportunities, strategic R&D-driven capabilities and milestones, synergistic relationships among various entities both within and outside the country, and mechanisms for capacity building and financial support. We recommend the formation of a Bioenergy Planning and Coordination Board, with representatives from government, the technology missions, academia, the energy industry, labour and civil society.

We recommend that the initiative described in (2) above be pursued most productively by a process that is simultaneously broad in its representation and focused in its mission. We suggest that the effort described in recommendation 2 be undertaken in parallel with the analysis addressed in recommendation 1.

As mentioned at the start of this article, South Africa essentially dropped R&D for biomass processing about a decade ago. The post-apartheid government has paid special attention to the needs of the country's previously disadvantaged majority as well as to the health of the economy in a rapidly changing world. Great strides have been made, yet persistent challenges remain. Responding to many of these challenges would be served by measures that address rural job creation, development of new industries, improved balance of payments, and wiser use of the natural resource base. It is appropriate, therefore, that in today's South Africa, investing in R&D for biomass processing, which has been of secondary importance in recent years, should become a more prominent focus once again.

Received 4 December. Accepted 20 December 2003.

1. McLaughlin S.G, De La Toree Ugarte D.G., Garten C.T., Lynd L.R., Sanderson M.A., Tolbert V.R. and Wolf D.D. (2002). High-value renewable energy from prairie grasses. *Environ. Sci. Technol.* **36**, 2122–2129.
2. Patterson-Jones J.C. (1989). *The Biological Utilization of Bagasse, a Lignocellulosic Waste. S. Afr. Natl Sci. Prog. Rep.* **149**. CSIR, Pretoria.
3. Potgieter H.J. (1981). Biomass conversion in South Africa. *Adv. Biochem. Eng.* **20**, 181–187.
4. Watson T. G. and Nelligan I. (1983). Pilot scale production of cellulase by *Trichoderma reesei* RUT C-30. *Biotechnol. Lett.* **5**, 25–28.
5. Du Preez J.C., Bosch M. and Prior B.A. (1986). Xylose fermentation by *Candida shehatae* and *Pichia stipitis*: effects of pH, temperature, and substrate concentration. *Enzyme Microb. Technol.* **8**, 360–364.
6. Du Preez J.C., Prior B.A. and Monteira A.M.T. (1984). The effect of aeration on xylose fermentation by *Candida shehatae* and *Pachysolen tannophilus. Appl. Microbiol. Biotechnol.* **19**, 261–266.
7. Watson N.E., Prior B.A., Du Preez J.C. and Lategan P.M. (1984). Factors in acid treated bagasse inhibiting ethanol production from D-xylose by *Pachysolen tannophilus. Enzyme Microb. Technol.* **6**, 447–450.
8. Lynd L.R., Weimer P.J., van Zyl W.H. and Pretorius I.S. (2002). Microbial cellulose utilization: fundamentals and biotechnology. *Microbiol. Mol. Biol. Rev.* **66**, 506–577.
9. Lynd L.R., Wyman C.E. and Gerngross T.U. (1999). Biocommodity engineering. *Biotechnol. Prog.* **15**, 777–793.
10. Sheehan J. and Himmel M. (1999). Enzymes, energy, and the environment: a strategic perspective on the U.S. Department of Energy's research and development activities for bioethanol. *Biotechnol. Prog.* **15**, 817–827.

11. Wyman C.E. (1999). Biomass ethanol: technical progress, opportunities, and commercial challenges. *Annu. Rev. Energy Environ.* **24**, 189–226.
12. Wyman C.E. (2003). Potential synergies and challenges in refining cellulosic biomass to fuels, chemicals, and power. *Biotechnol. Prog.* **19**, 254–262.
13. Zaldivar J., Nielsen J. and Olsson L. (2001). Fuel ethanol production from lignocellulose: a challenge for metabolic engineering and process integration. *Appl. Microbiol. Biotechnol.* **56**, 17–34.
14. Morris D. and Ahmed I. (1992). *The Carbohydrate Economy.* Institute of Local Self-Reliance, Washington, D.C.
15. Johannson S.B., Kelly H., Reddy A.K.N. and Williams R.H. (1993). A renewables-intensive global energy scenario. In *Renewable Energy,* eds S.B. Johannson, H. Kelly, A.K.N. Reddy and R.H. Williams, pp. 1071–1142. Island Press, Washington, D.C.
16. Kassler P. (1994). *Energy for Development.* Shell Petroleum International, London.
17. Lynd L.R., Cushman J.H., Nichols R.J., and Wyman C.E. (1991). Fuel ethanol from cellulosic biomass. *Science* **251**, 1318–1323.
18. Lynd L.R. (1996). Overview and evaluation of fuel ethanol production from cellulosic biomass: technology, economics, the environment, and policy. *Annu. Rev. Energy Environ.* 21, 403–465.
19. Lynd L.R., H. Jin, J.G. Michels, C.E. Wyman and B. Dale (2003). *Bioenergy: Background, potential, and policy.* Center for Strategic and International Studies, Washington, D.C. Http://www.csis.org/tech/Biotech/
20. Anon. (1995). *Biotechnology for the 21st Century: New Horizons.* Biotechnology Research Subcommittee, Committee on Fundamental Science, National Science and Technology Council, Office of Science and Technology Policy, Washington, D.C. Http://www.nal.usda.gov/ bic/bio21/
21. Anon. (1999). *Biobased Industrial Products: Priorities for research and commercialization.* National Research Council. National Academy Press, Washington, D.C.
22. Anon. (1998). Chem industry begins restructuring in the wake of biotech revolution. *Chem. Mark. Rep.* **254**, 22–23.
23. Thayer A. (1998). Living and loving life sciences. *Chem. Eng. News* **76**, 17–24.
24. Anon. (2003). The greening of biotechnology. *The Economist,* 27 March.
25. Frey, W.A. (2003). Biotech companies say industrial biotechnology is key to future growth. *Global Ethics Monitor*, February 26, New York. Http://www.globalethicsmonitor.com/
26. Anon. (2002). Renewable energy. Http://www.bp.com/environ_social/environment/renewable.asp
27. Anon. (2003). Alternative energy sources. Http://www.shell.com/home/Framework?siteId=rw-br&FC2=/rw-br/html/iwgen/about_shell/other/zzz_lhn.html&FC3=/rw-br/html/iwgen/about_shell/other/other_energy_0616.html
28. Anon. (2002). Shell invests in green fuel technology. Press Release, 8 May, Iogen Corporation. Http://www.iogen.com
29. Manuel T.A. (2001). Budget speech to Parliament. National Treasury, Pretoria.
30. Anon. (2002). *White Paper on the Promotion of Renewable Energy and Clean Energy Development. Part One: Promotion of Renewable Energy.* Department of Minerals and Energy, Pretoria.
31. DeLucchi M.A. (1991). *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity.* Argonne National Laboratory, Argonne, IL.
32. Anon. (1996). Report to the President of the Interagency Steering Committee on the Outcome of the Deliberations of the Policy Dialogue Advisory Committee to Assist in the Development of Measures to Significantly Reduce Greenhouse Gas Emissions from Personal Vehicles. The White House, Washington, D.C.
33. Tyson K. S., Riley C.J. and Humphreys K.K. (1993). Fuel cycle evaluations of biomass-ethanol and reformulated gasoline. NREL/TP-463-4950. Office of Transportation Technologies, Department of Energy, Washington, D.C.
34. Wang M., Saricks C. and Santini D. (1999). Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. ANL/ESD-38. Center for Transportation Research, Argonne National Laboratory, Argonne, IL.
35. Lugar R.G. and Woolsey R.J. (2000). The new petroleum. *Foreign Affairs* **78**, 88–102.
36. Christison B. (2002). Oil and the Middle East – Why U.S. policy has to change. *ASPO-ADAC Newsl.* no. 17. Http://www.energiekrise.de/e/news/aspo.html
37. Woolsey R.J. (2002). Defeating the oil weapon. *Commentary,* September 1, **114**(2), 29–34.
38. Anon. (2003). Trade by chapters. Jan 2003 – Aug. 2003. Department of Trade and Industry. Http://www.thedti.gov.za/econdb/raportt/rapch.html
39. Campbell C.J. (2002). Peak oil: An outlook on crude oil depletion. *MBendi: Information for Africa,* 18 February. Http://www.mbendi.com/indy/oilg/p0070.htm
40. Deffeyes K.S. (2001). *Hubberts Peak – The impending oil shortage.* Princeton University Press, Princeton, NJ.
41. Kerr R.A. (1998). The next oil crisis looms large – and perhaps close. *Science* **218**, 1128–1131.
42. Sparks A. (2003). *Beyond the Miracle: Inside the New South Africa.* Jonathan Ball Publishers, Johannesburg.
43. Petrulis M., Sommer J. and Hines F. (1993). *Ethanol Production and Employment.* USDA Economic Research Service, Agriculture Information Bulletin No. 678, July 1993. Washington, D.C.
44. Yergin D. (1992). *The Prize: The epic quest for oil, money and power.* Simon and Schuster, New York.
45. Hawkins P., Lovins A. and Lovins L.H. (1999). *Natural Capitalism: Creating the next industrial revolution.* Little, Brown, Boston.
46. Grobler L.J. and den Heijer W.I.R. (2001). The potential needs and barriers to emission trading, joint implementation and the clean development mechanism in South Africa. *J. Energy S. Afr.,* **12**, 377–387.
47. Anon. (2002). US Department of Energy, Energy Information Administration, Report on South Africa, February 2002 Http://www.eia.doe.gov/emeu/cabs/safrica.html
48. Anon. (2003). South Africa: Extract from the Survey of Energy Resources 2001. World Energy Council, Energy Information Centre Report on South Africa. Http://www.worldenergy.org/wec-geis/edc/countries/SouthAfrica.asp
49. Anon. (2003). South African Petroleum Industries Association (SAPIA). Http://www.sapia.org.za
50. Anon. (2003). South African Renewable Energy Resource Database. Http://www.csir.co.za/environmentek/sarerd/biomass.html
51. Wienese A. (2001). Co-generation in the South African sugar industry. In *DME, DANCED, 2001 Bulk Renewable Energy Independent Power Producers in South Africa,* January 2001.
52. Turn S.Q. (1999). Biomass integrated gasifier combined cycle technology: application in the cane sugar industry. *Int. Sugar J.* **101**, 267–280.
53. Sheehan J., Aden A., Riley C., Paustain K., Brenner J., Killian K., Cushman J., Walsh M. and Nelson R. (2002). Is biomass part of a sustainable energy future? Adventures in cyber farming. Presented at the Meeting of the AIChE, Indianapolis, Indiana. 7 November 2002.
54. Lynd L.R., Lyford K., South C.R., Van Walsum G.P. and Levenson K. (2001). Evaluation of paper sludges for amenability to enzymatic hydrolysis and conversion to ethanol. *TAPPI J.* **84**, 50. [full text at http://www.tappi.org]
55. Marrison C.I. and Larson E.D. (1996). A preliminary analysis of the biomass energy production potential in Africa in 2025 considering projected land needs for food production. *Biomass and Bioenergy* **10**, 337–351.
56. Carpentieri A.E., Larson E.D. and Woods J. (1993). Future biomass-based electricity supply in Northeast Brazil. *Biomass and Bioenergy* **4**, 149–173.
57. Berndes G., Hoogwijk M. and van den Broek R. (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy* **25**, 1–28.
58. Wolf J., Bindraban P.S., Luijten J.C. and Vleeshouwers L.M. (2003). Exploratory study on the land area required for global food supply and the potential global production of bioenergy. *Agric. Syst.* **76**, 841–861.
59. Zimmermann H.G., Moran V.C. and Hoffmann J.H. (in press). Biological control in the management of invasive alien plants in South Africa, and the role of the Working for Water programme. *S. Afr. J. Sci.* **100**.
60. Marais C., van Wilgen B.W. and Stevens D. (in press). The clearing of alien plants in South Africa: a preliminary assessment of costs and progress. *S. Afr. J. Sci.* **100**.
61. Theron J.M. (2003). An inventory of utilisable biomass loads in invading alien plant stands and its consequences for management. *Inaugural Research Symposium, Working for Water Programme,* 19–21 August 2003, Kirstenbosch Botanical Gardens. Working for Water Programme, Cape Town. See also: Turpie J. (in press). The role of resource economics in the control of invasive alien plants in South Africa. *S. Afr. J. Sci.* **100**.
62. Anon. (2003). Crop production estimates. Department of Agriculture, Pretoria. Http://www.nda.agric.za
63. Bhatt M. S. and Rajkumar N. (2001). Mapping of combined heat and power systems in cane sugar industry. *Appl. Thermal Engng* **21**, 1707–1719.
64. Anon. (2002). *South African Forestry Facts for the Year 1999/2000.* Department of Water Affairs and Forestry. Pretoria. [Full text at http://www.forestrysa.co.za]
65. Hunt J. (2002). South Africa: Imports, exports drop but production rises: South Africa. Paperloop.com. Http://www.paperloop.com/db_area/archive/ppi_mag/2002/0207/africa_south_africa.html
66. Collings J. (2002). *Mind Over Matter – The Sasol Story: a half century of technological innovation.* Sasol Corporate Affairs, Johannesburg.
67. Anon. (2003). Brazilian sugar and ethanol industry. *Uniao da Agroindustria Canavieria de São Paolo,* May 2003.
68. Anon. (2003). Quarterly Market Outlook, International Sugar Organisation, London, May 2003.
69. Anon. (2003). Breakthrough for biodiesel. *Renewable Energy World* **6**, 24, Sep-Oct 2003.
70. *South Africa's National Research and Development, Strategy.* Department of Science and Technology, Pretoria; 2002.